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Optical imaging of the prefrontal activity in joint attention experience

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Abstract: Functional near-infrared spectroscopy (fNIRS) was used to measure the prefrontal activity in joint attention experience. 16 healthy adults participated in the experiment in which 42 optical channels were fixed over the anterior prefrontal cortex (aPFC), dorsolateral prefrontal cortex (DLPFC), inferior frontal gyrus (IFG) and a small anterior portion of the superior temporal gyrus (STG). Video stimuli were used to engender joint or non-joint attention experience in observers. Cortical hemodynamic response and functional connectivity were measured and averaged across all subjects for each stimulus condition. Our data showed the activation in joint attention located in the aPFC and DLPFC bilaterally, but dominantly in the left hemisphere. This observation, together with the previous findings on infants and children, provides a clear developmental scenario on the prefrontal activation associated with joint attention process. In the case of non-joint attention condition, only a small region of the right DLPFC was activated. Functional connectivity was observed to be enhanced, but differently in joint and non-joint attention condition.

OCIS codes: (170.2655) Functional monitoring and imaging; (170.3880) Medical and biological imaging; (170.5380) Physiology.

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1. Introduction

Joint attention is a communication process in which one individual directs another individual's attention towards an object or event by eye-gazing, pointing, or other gestural indications. Behavioral observation on infants has shown that infants have the ability to

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follow other's eye gaze in their first year of life, indicating joint attention skill develops earlier than language skill [1]. Joint attention, as a fundamental capacity of a human individual coordinating attention with a social partner, is important for the development of various cognition and social competences, including language acquisition, information processing and intelligence quotient [2,3]. With impaired joint attention capacity, the development of learning skill of an individual would be affected or impeded. Considerable evidences have suggested children with autism are impaired in joint attention capacity [4–7]. Meanwhile, the social relatedness and relationships of adolescents and even adults would be impaired if they lack of the ability to share attention in social interactions.

In addition to behavioral observation, neuroimaging methods were used to reveal brain substrate underlying joint attention process [8–12]. The physiological information obtained from imaging techniques, together with behavioral observation, would help psychologists or neuroscientists achieve a more comprehensive understanding on joint attention. The mostly used neuroimaging techniques in joint attention study are electroencephalography (EEG) and functional magnetic resonance imaging (fMRI), the former technique was used for infants [8,9], while the later for adults [10–12]. The convergent evidence from joint attention studies on subjects at different developmental stage (infancy, adulthood) with different imaging modalities (EEG, fMRI) show that joint attention process is associated with the anterior and posterior attention system [10,13,14], the former system includes the frontal eye fields, anterior cingulate and orbital prefrontal cortex, while the later includes the superior parietal lobule, inferior parietal lobule, middle temporal gyrus, and superior temporal gyrus. However, interestingly there is a striking distinct between infants and adults in recruiting cortical area in joint attention: the aPFC [or Brodmann Area (BA) 10] is involved in joint attention process in adults [10,12], whereas it is not in infants [9,13,14].

Very recently functional near-infrared spectroscopy (fNIRS) was introduced to studying joint attention on infants [15], children [16] and adults [17,18]. fNIRS is a novel non-invasive functional imaging technique [19–22]. By using near-infrared light as probe to interrogate cortex through the intact scalp and skull, this optical technique provides cerebral hemodynamic parameters, e.g. oxy-hemoglobin (HbO) and deoxy-hemoglobin (Hb) concentration. In a typical fNIRS measurement such as a motor task experiment [19], activation regions show enhanced HbO and reduced Hb as compared with their baseline values. Therefore, the term of activation in fNIRS means enhanced HbO (and reduced Hb). Studies by using fMRI and fNIRS concurrently have demonstrated that fMRI BOLD signal is positively correlated with the concentration change of HbO (or Δ[HbO]) or negatively correlated with the concentration change of Hb (or Δ[Hb]) [23], implying the activation regions identified by fMRI are likely those identified by fNIRS.

An fNIRS study of prefrontal response to joint attention on 5-month-old infants showed significant activation in a small region of the left DLPFC (BA 9), no activation in the aPFC [15], which was in line with the previous EEG findings [9,13,14]. A recent fNIRS study of joint attention on children (with and without autism) conducted by our group showed activation in the DLPFC and its adjacent aPFC bilaterally for the children without autism (20 typical developing children with age ranging from 6 to 10 years old) [16]. The extent of the activation in the aPFC was small. This result is in agreement partially with the fMRI data on adults [10,12] and partially with the fNIRS and EEG data on infants [9,13–15]. Aside from these studies on infants and children, only one fNIRS work was reported on investigating adult prefrontal response to joint attention [17]. In this study, 11 adults participated in the experiment in which the prefrontal responses were recorded by 8 optical channels covering an area of about 3 cm × 7 cm. The change in HbO was indeed observed in joint attention task, but surprisingly, all the 8 optical channels showed reduced HbO, which in general could not be interpreted as the activation in fNIRS measurement. Since the enhanced HbO (or the reduced Hb) is positively correlated with fMRI BOLD signal, the observation of the reduced HbO in the prefrontal cortex is hardly consistent with the fMRI finding [10].

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The aPFC of human plays an important role in integrating information concerned with two or more separate cognitive operations at an abstract level [24]. Joint attention task is exactly the case where the brain needs to integrate perceptual processes associated with monitoring the direction of other's attention, with those controlling the individual's own direction of attention [10]. This explains why the aPFC could be involved in joint attention process. We suppose that the aPFC in infancy does not mature yet, thus the infant aPFC is not capable of handling the higher-order integration task. While in the childhood when the aPFC gets substantial development, to a certain degree, the aPFC is able to process the integration task, thus involved partly in joint attention. Since in the adulthood the aPFC matures completely, it is supposed to take more critical role in the integration process associated with joint attention. Therefore, we believe the aPFC of adult is not only activated, but the activation extent is also larger than that of children, which can be revealed by fNIRS.

Brain is organized and functioning in networks, which implies in a specific task the functional relevant cortical regions nearby or even remote work coherently. To achieve a complete understanding on the brain substrate involved in joint attention process, it is useful to know not only the activation regions, but also the possible functional connectivity between these regions. However, thus far, there is only one study with fNIRS reporting functional connectivity in the prefrontal cortex in joint attention [18]. In this study, data from only 8 optical channels were used to derive the connectivity, thus only a few connectivity parameters could be evaluated. With such a small number of measurement channels, it is impossible to obtain details about the connectivity across various regions of the prefrontal cortex.

In the present study, we use a multichannel continuous-wave (CW) fNIRS to measure the adult prefrontal activity in joint attention experience. 42 optical channels are located over a wider extent (6 cm × 24 cm) of the prefrontal cortex, including the aPFC, DLPFC, IFG and a small anterior portion of the STG. 16 healthy adults participated in this study. With more optical channels, a larger cortical area can be interrogated. Since the task-induced hemodynamic change may include the enhanced and the possible reduced HbO signal, a large probing area could be useful for catching various (enhanced or reduced) signals arising from different cortical regions. The main goal of this study is to test our hypothesis that the adult aPFC should be activated in terms of the enhanced HbO (not the reduced HbO) in joint attention, which concurs with the previous fMRI findings. In addition to that, the activation extent in the aPFC is supposed to be larger for adults than for children, which can also be verified. Results from this study on adults, together with those on infants and children, may provide a developmental scenario on the role of the aPFC in different developmental stages in processing joint attention (e.g. from infancy when the aPFC is not involved, to childhood when the aPFC is partly involved and adulthood when the aPFC is actively involved). Meanwhile, since more optical channels are used, it is feasible to identify the prefrontal connectivity and its alteration caused by joint attention task. We believe the prefrontal functional network and its response to joint attention may provide additional information for understanding the brain substrate involved in joint attention process.

2. Methods

2.1 Experimental setup

A commercial CW fNIRS image system (FOIRE-3000, Shimadzu Corporation, Kyoto, Japan) was used to measure the concentration changes in hemodynamic parameters (HbO and Hb). The optodes, including 14 sources and 13 detectors, building up 42 channels (see Fig. 1(b)), were fixed over the forehead. The inter-optode distance was 3 cm. The whole imaging area was 6 cm × 24 cm, including the aPFC, DLPFC, IFG and a small anterior portion of the STG. When fixing the optodes, the EEG 10-10 electrode placement system [25] was referenced. In this experimental study, the sampling frequency was 14.3 Hz.

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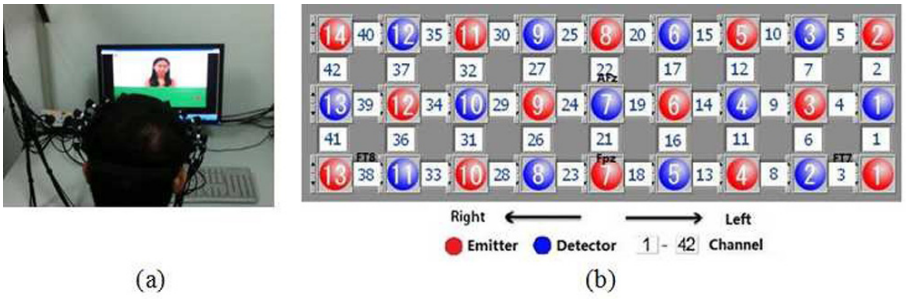

Fig. 1. (a) Photo of a subject watching the computer monitor delivering the video stimuli. (b) The arrangement of the optodes with reference to the 4 EEG sites (FPz, AFz, FT7 and FT8) of the international 10-10 system.

2.2 Subjects and experimental protocol

16 healthy adult subjects (8 males) were enrolled in the study. The subjects ranged in age from 23 to 26 years old (24.4 ± 0.9 years).They were all right-handed, had no history of neurological or psychiatric disease. Before experiments, they were all informed about the measurement procedure, and a written consent was obtained from each of them.

In the present study, the video developed for our previous work [16] was used. This video is similar to that used in the reference [10]. When the subject watched the video, it engendered an experience of joint attention or non-joint attention in the observer. During the measurement, the subject sat in a comfortable chair watching the video displayed in a 19-inch computer monitor located 70 cm away from the subject eyes (see Fig. 1(a)). The subject was asked to keep the head still, only shift gaze by eye movement. To engender an experience of joint or non-joint attention in observer, each subject was required to successively watch 8 video clips lasting 8 minutes. Each video clip consisted of 30 s black screen (rest condition) followed by 30 s joint attention (or non-joint attention) stimuli. The 8 video clips were played in a pseudo-random order, but always included 4 joint attention and 4 non-joint attention blocks. For joint attention condition, the person in the video moved her head and eyes towards a horizontally moving red dot, whereas the subject moved only eyes towards the dot (see Fig. 2(a)). For non-joint attention condition, the subject gazed the moving red dot without any coordination with the person in the video (see Fig. 2(b)). The experimental protocol was approved by the Institutional Review Board of South China Normal University.

2.3 Data analysis

The raw 8-min temporal hemodynamic data (HbO and Hb) of each subject were first detrended by using a second order polynomial fit to remove the first- and second-order drift [26]. Then a band-pass (0.004-0.08 Hz) filter was used to get rid of task-irrelevant physiological interferences such as those originated from cardiac pulsations, reparations and low frequency arterial blood pressure oscillations. Since the 8-min data contain 8 blocks of tasks (4 joint and 4 non-joint attention's), the central frequency of expected response is 1/60 s = 0.0167 Hz, within the band pass range. After the band-pass filter, the data were down-sampled to 0.5 Hz and then transformed to Z scores. The Z scores were block-averaged separately for each channel and each condition (joint or non-joint attention). We defined the hemodynamic response as the change of the mean Z scores between the task and rest period. Finally, the group-averaged hemodynamic response of each channel and the correlation matrix of all channel pairs were computed for each condition. Each element of the correlation matrix was the temporal Pearson correlation coefficient of the corresponding channel pair. The connectivity strength for the channel pair was reflected by its correlation coefficient. To visualize the activation patterns, false color maps were generated, in which each pixel value represented the hemodynamic response in the task. The group-averaged correlation matrix

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was also visualized with a false map for each condition. For statistical analysis, the Student T-test and multiple comparison correction based on Benjamini false discovery rate (FDR) [27] were used.

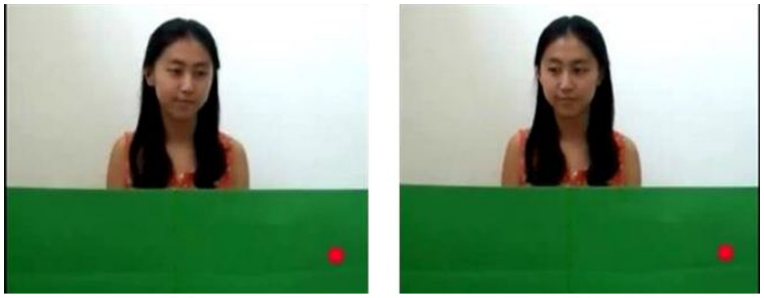

Fig. 2. Screenshots of video chips used as stimuli to engender joint attention (a) and non-joint attention (b) experience. The viewer (subject) experienced joint attention when watching the moving red dot together with the person on the screen. The viewer (subject) experienced non-joint attention when simply watching the moving dot without any coordination with the person on the screen.

Since changes in systemic hemodynamic parameters such as heartbeat rate (HR) and respiration rate may make contributions to the measured changes in the cortex, these parameters should be monitored during measurements, especially those involved in tasks. Because performing task may induce change in systemic hemodynamics. In this study, we obtained these systemic parameters by analyzing the time series of channel-averaged HbO. For determining the HR, a band pass filter (0.4-2 Hz) was applied to the detrended HbO data, and then by using the fast Fourier transform (FFT), we obtained the HR. While for estimating the respiration rate, a band pass filter (0.2-0.4 Hz) was used. Since each condition session lasted 30 s, the time window for the FFT was selected to be 30 s.

3. Results

Figure 3 shows the group-averaged HbO response patterns in the measured area for joint (Fig. 3(a)) and non-joint (Fig. 3(b)) attention condition. Joint attention caused bilateral activation in the aPFC and DLPFC. Significant ($p<0.05$ after the FDR correction) activation regions are circled in red in Fig. 3(a), include one in the aPFC, and two in the joint areas of the aPFC + DLPFC. The activation region in the aPFC was covered by channel 13, 18 and 23; while the joint areas of the aPFC + DLPFC were covered by channel 12, 14 and 29. Slightly stronger activation amplitude and larger activation extent were observed in the left hemisphere (see regions circled in red in Fig. 3(a)). Non-joint attention caused only a small activation region (channel 30) in the right DLPFC (Fig. 3(b)). In contrast to joint attention, the activation amplitude was also smaller. Interestingly, in addition to see activation regions, one can also see pronounced deactivation regions (see Fig. 3(a), two regions circled in blue) in the IFG + STG bilaterally, where the HbO response in joint attention task is smaller than the rest condition. These deactivation regions were covered by channel 4, 6, 36, 38, and 39. Due to very low signal-to-noise level of Hb, no significant response of Hb was observed in either joint attention or non-joint attention condition, thus the data of Hb were not presented.

The group-averaged HR was 76.9 ± 10.1 min^{-1} for the rest, 74.2 ± 9.9 min^{-1} for joint attention, and 74.1 ± 9.7 min^{-1} for non-joint attention condition. The Student T-test showed change in HR was significant between the rest and joint attention ($p = 0.0199$ after the FDR correction), and between the rest and non-joint attention ($p = 0.0036$ after the FDR correction). There was no significant HR difference between the two task conditions (joint and non-joint attention). This implied that both tasks caused slight, but significant HR deceleration. The group-averaged respiration rate was 16.8 ± 1.6 min^{-1} for the rest, 16.7 ± 1.6

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min^{-1} for joint attention, and 17.5 ± 2.1 min^{-1} for non-joint attention condition. No statistically difference was observed between the three conditions.

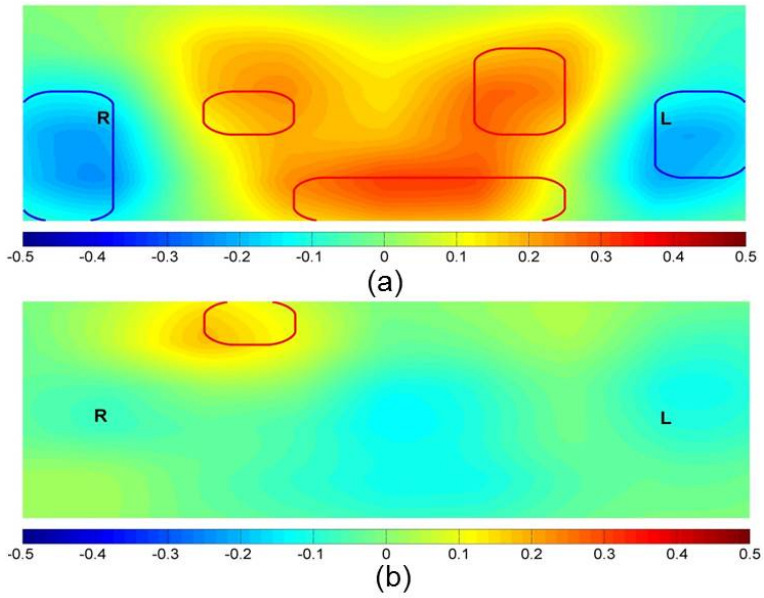

Fig. 3. Group-averaged HbO response patterns in joint (a) and non-joint (b) attention condition. The capital letter R (or L) in each map indicates the right (or left) hemisphere. The significant activation (in terms of enhanced HbO) regions are circled in red; while the significant deactivation (in terms of reduced HbO) regions are circled in blue. Threshold for significance was set at $P < 0.05$ after the FDR correction.

The temporal response to joint attention in the activation regions (those circled in red in Fig. 3(a)) and the deactivated regions (those circled in blue in Fig. 3(a)) were also calculated and presented in Fig. 4. It took about 22 s for the activation (or deactivation) to reach its maximum (or minimum).

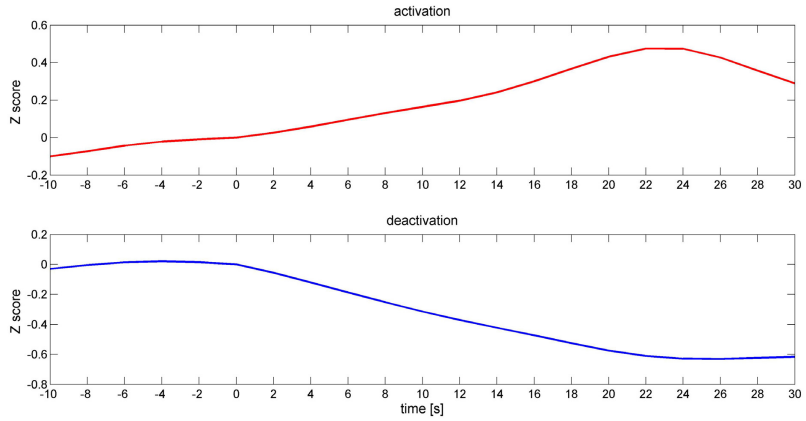

Fig. 4. Temporal responses to joint attention in the activation region (red line) and deactivation region (blue line). Joint attention task started at t = 0 s, t<0 was the rest period.

Figure 5 shows correlation matrices for the 3 conditions: the rest, joint attention, and non-joint attention. It can be visually identified there are 3 strongly correlated clusters in each correlation map: Cluster I grouped by channel 1-9, Cluster II by channel 10-32, and Cluster

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III by channel 33-42. In fact, Cluster I is also correlated with Cluster III. These 2 clusters of channels located over the bilateral language area (IFG + STG), where the spontaneous activity has been demonstrated to be strongly correlated [28,29]. Channels of Cluster II located primarily over the bilateral aPFC and DLPFC, indicating the activities in these two areas were highly synchronized. The correlation coefficients were altered by either task (joint or non-joint attention) towards enhanced network connectivity (see Fig. 4(b) and 4(c)). This implies during the task period, the cortical activity associated with the task became more synchronized. Interestingly, enhanced connectivity was also observed in the bilateral language areas where the deactivation was observed in joint attention condition.

Table 1 and Table 2 list channel pairs and their correlation coefficients which were enhanced significantly for joint and non-joint attention condition, respectively. Figure 4(b) and 4(c) look similar; however, the connectivity enhanced is different, which is revealed in detail in the two tables.

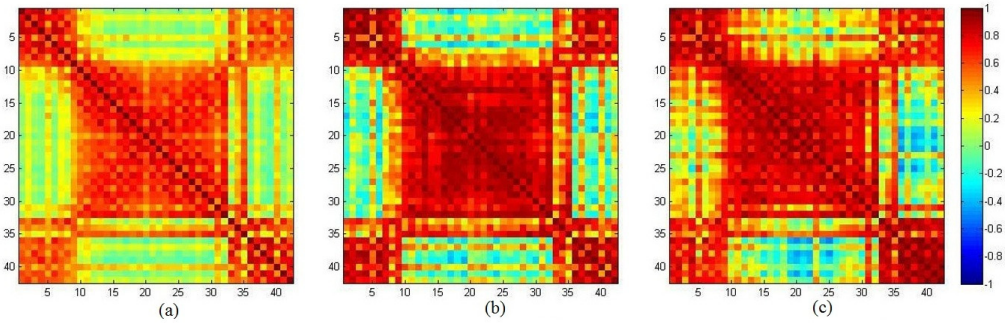

Fig. 5. Group-averaged correlation matrices of HbO for all channel pairs for the rest (a), joint attention (b), and non-joint attention (c) condition. Each pixel value represents the correlation coefficient for the corresponding channel pair. Each number (1-42) in x- or y-axis indicates numbering of the optical channel.

Table 1. Enhanced connectivity identified by contrast of joint attention versus rest

	Channel pair	Correlation coefficient (rest)	Correlation coefficient (joint attention)	P (FDR corrected)
Inter-hemispheric	(1,38)	0.5633	0.9188	0.0161
	(4,38)	0.5883	0.9109	0.0147
	(6,38)	0.6522	0.9427	0.0160
	(13,25)	0.5561	0.8953	0.0021
	(14,32)	0.7331	0.8924	0.0159
	(16,25)	0.5142	0.8849	0.0139
	(17,23)	0.6043	0.9174	0.0121
	(17,25)	0.6682	0.9207	0.0165
	(17,28)	0.5647	0.8735	0.0245
	(18,25)	0.5763	0.9110	0.0068
Intra-hemispheric (left)	(1,6)	0.8303	0.9774	0.0042
	(4,6)	0.8578	0.9732	0.0080
	(7,9)	0.7562	0.9228	0.0102
	(13,17)	0.6729	0.9109	0.0171
	(15,18)	0.5493	0.8638	0.0149
Intra-hemispheric (right)	(21,25)	0.5727	0.9018	0.0105
	(23,25)	0.5480	0.8956	0.0071
	(25,28)	0.4958	0.8871	0.0035
	(25,33)	–0.0535	0.4338	0.0245

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Table 2. Enhanced connectivity identified by contrast of non-joint attention versus rest

	Channel pair	Correlation coefficient (rest)	Correlation coefficient (joint attention)	P (FDR corrected)
inter-hemispheric	(1,23)	0.0357	0.4589	0.0245
	(10,23)	0.4653	0.8268	0.0260
	(10,27)	0.5447	0.8321	0.0146
	(10,30)	0.5732	0.8705	0.0179
	(11,23)	0.5449	0.8840	0.0130
	(12,27)	0.7047	0.9387	0.0018
	(12,30)	0.6523	0.9133	0.0151
	(20,30)	0.5131	0.7994	0.0240
Intra-hemispheric (left)	(1,8)	0.6530	0.8949	0.0149
	(1,14)	0.0178	0.4331	0.0081
	(1,16)	0.0420	0.5087	0.0141
	(3,14)	0.0468	0.5012	0.0236
	(12,19)	0.6329	0.8981	0.0150
	(12,20)	0.5185	0.8665	0.0223
	(15,20)	0.5304	0.8952	0.0081
	(15,22)	0.6537	0.9022	0.0240
	(19,22)	0.8075	0.9531	0.0158
Intra-hemispheric (right)	(34,39)	0.6299	0.8975	0.0133

4. Discussion

In line with the previous fMRI findings on adults [10,12], a large region in the aPFC was observed to be activated (in terms of the enhanced HbO) in joint attention (see Fig. 3(a)). The significant activation region was covered by three channels (channel 13, 18 and 23). Interestingly, this activation was not present in either infants [15] or children (see Fig. 6 replotted from the data in [16]). Apart from this striking difference, the DLPFC was observed to be involved in joint attention process for all human subjects at a wide range of developing stages (infants, children, and adults). Nevertheless, the extent of DLPFC involved was different between different developing stages. The DLPFC includes BA 9 and BA 46. For infants, only a small region in the left DLPFC (BA 9) was activated. In fact, this small region was covered by only one channel with an inter-optode separation of 2.5 cm [15]. For children, the activation regions included bilateral joint areas of DLPFC + aPFC, consisting of left BA 9, bilateral BA 46 and parts of BA 10 (see Fig. 6). These activation regions were covered by five channels in total, one in the right hemisphere (channel 29), and the other four in the left hemisphere (channel 9, 12, 14 and 15) locating over the left BA 9 and the joint area of BA 46 and BA 10. For adults, three channels showed activation in the left BA 9 (channel 12) and bilateral joint areas of BA 46 and BA 10 (channel 14 and 29). Taking the aPFC activation region into account, we observed in adults six optical channels in total showed activation in joint attention. Therefore, a developmental scenario on the prefrontal activation concerned with joint attention process was revealed by fNIRS: from a single small region in the left DLPFC (infants) to the bilateral large area in the DLPFC, as well as parts of adjacent aPFC (children) and the larger bilateral area in the DLPFC and aPFC (adults). Therefore, with the development of cortices, the cortical area involved in joint attention process becomes larger and larger. On the other hand, higher-order cognition, but late maturing area of the aPFC (or BA 10) is eventually involved in joint attention process.

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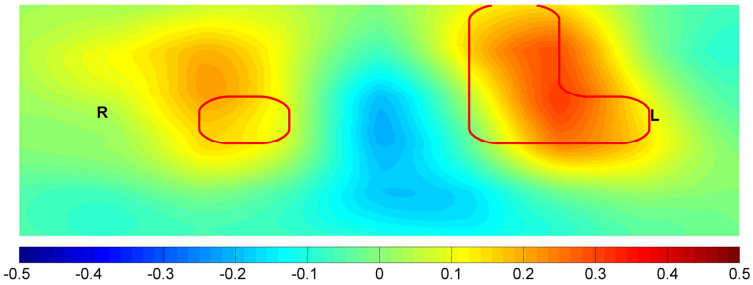

Fig. 6. Group-averaged HbO response patterns in joint attention in children (age: 8.1 ± 1.3 years old). The capital letter R (or L) in each map indicates the right (or left) hemisphere. The significant activation (in terms of enhanced HbO) regions are circled in red, including channel 9, 12, 14, 15 and 29. Threshold for significance was set at $P < 0.05$ after the FDR correction. This is a replot from the data in ref [16] for typical developing children, with the method same as that used in Fig. 3. Note that in ref [16], only a part of optical channels (22 out of 42) located centrally were used for presenting the data.

Task-related cortical activity can be modulated by systemic hemodynamic variations induced by the task. For example, HR modulates blood flow and blood volume in the artery system, while respiration induces change in venous blood volume. Therefore, if these systemic parameters are task dependent, the measured cortical response to the task might be affected by these parameters. In this study, no difference in respiration rate was observed across the three conditions. However, compared with the rest, HR was observed to decrease by 3.5% in both joint and non-joint attention conditions. Systemic parameters such as HR and respiration rate were not reported in the previous studies using video stimuli to engender joint attention experience [10,16–18]. In fact, a slight HR deceleration was previously found when subject performed visual task, which could be explained as that "stimulus intake (outward directed attention) produces heart rate deceleration associated with cortical activation" [30]. Therefore, it was not a surprise to see the decrease in HR in our joint attention experiment. This systemic change could cause a slight decrease in the blood flow and blood volume in the brain and scalp, resulting in an underestimate in the HbO measured from each channel in our experiment. The main effect of this underestimate was likely to reduce the HbO response level across the whole imaging area. On the other hand, the fact that the HR deceleration was almost same for joint and non-joint attention conditions, whereas the activation pattern was completely different between these two conditions, may indicate the slight change in HR had no pronounced effect on the activation patterns for joint and non-joint attention conditions.

A number of studies have already demonstrated there exit deactivation regions in the non-stimulated cortical area [31–33], indicated by either negative BOLD signal or reduced HbO as compared with the corresponding baseline value. The deactivation might originate from two aspects: first, there indeed exits inhibition of neural activity in response to a certain task; second, the blood 'stealing' effect makes contribution to the negative BOLD or the reduced HbO signal. In the present study, significant deactivation was observed in the bilateral language areas. These language areas are primarily responsible for language generation and comprehension, have no definite role in processing joint attention. Thus the deactivation observed might come from the blood 'stealing' effect, which is an effective way to balance the enhanced blood supply to the adjacent or neighboring activation regions (such as the aPFC and DLPFC) involved in joint attention task. As non-stimulated areas, the bilateral language areas were probably involved passively in the task. Yet despite that, the connectivity in these regions was still enhanced in the task period, which might imply to meet the increased demand of blood supply to the activation area, the activity in each network involved in the task either actively or passively, need to be more synchronized.

Both fMRI [10] and fNIRS [15] studies have shown left-lateralized response in the frontal cortex to joint attention stimuli. We observed the activation in the bilateral aPFC and DLPFC.

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However, both activation amplitude and activation extent were larger in the left hemisphere than in the right hemisphere, which was in line with those previous findings.

In addition to a variety of functions such as strategic process, memory recall and various executions, the aPFC also plays a specific role in integrating the outcomes of two or more cognitive operations in the pursuit of a higher behavioral goal [24]. Joint attention process can be considered as such a case where the aPFC integrates perceptual processes associated with detecting the other's attention and controlling the self-attention into the joint attention process [10]. This explains why the aPFC can be involved in joint attention process. However, for infants or children, the aPFC is not involved (infants) or only involved partly (children), which seems not to affect significantly joint attention behavior, especially for children. A possible explanation is the DLPFC might take on the role of the aPFC in the aspect of information integration, especially when the aPFC does not mature yet. Indeed, there might exits overlapping function of the aPFC and DLPFC, which is manifested by the concurrent activation in the two areas in a variety of cognition tasks [24]. On the other hand, the two areas were observed to be functionally connected closely (see Fig. 4), which might support this interpretation. For non-joint attention, the aPFC is not involved. This is because the brain does not have to concurrently manipulate two perceptual processes and integrate the outcomes at an abstract level.

The functional network structure is similar for the 3 conditions (rest, joint- and non-joint attention), which is in line with the argument that the spatio-temporal spontaneous activities of neurons are only slightly modified by the external sensory input [34,35]. Despite the similar structure, the connectivity of the networks is quantitatively different for different conditions: first, compared with the rest, the altered connectivity is always enhanced, regardless of stimulation conditions; second, the enhanced connectivity is different for the two task conditions. For the condition of joint attention, the enhanced intra-hemispheric connectivity is observed in the both hemispheres; while for the condition of non-joint attention, the enhanced intra-hemispheric connectivity locates almost in the left hemisphere, except one (corresponding to the channel pair (34, 39)) in the right hemisphere (see Table 2). In addition, the enhanced connectivity for joint attention condition distributes more densely and symmetrically in the two hemispheres, as compared with non-joint attention condition.

5. Conclusions

We used a multi-channel fNIRS system to study adult prefrontal hemodynamic activation caused by joint and non-joint attention task. 42 optical channels were used to cover a wider area (6 cm × 24 cm) over the aPFC, DLPFC, IFG and a small anterior part of the STG. Our data showed the two tasks induced distinct hemodynamic response patterns: joint attention caused activation in the bilateral aPFC and DLPFC, but dominantly in the left side in respect of larger activation extent and stronger activation amplitude; while non-joint attention elicited activation only in a small region of the right DLPFC. Our data, together with previous fNIRS studies on infants and children, provide a clear developmental scenario on prefrontal response to joint attention: from infancy to childhood and adulthood, the activation area involved becomes larger and larger, and extends towards the higher-order cognition region of the aPFC. Functional network structures look similar for the 3 conditions (rest, joint and non-joint attention); nevertheless, both tasks could quantitatively enhance the connectivity, even in regions where no significant hemodynamic change was observed. This may suggest the alteration in connectivity (coupled quantity) is more sensitive to the stimulation than the (uncoupled) hemodynamic signal itself. The enhanced connectivity is different for joint and non-joint condition, indicating perhaps two different sub-networks involved in the two different tasks, respectively. These observations may provide new evidences for better understanding the brain substrate underlying joint and non-joint attention process.

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Appendix

Nowadays there are various techniques for fNIRS, such as time-domain, frequency domain, and CW technique. In general, most of commercial CW systems do not provide absolute measures on hemodynamic parameters. For example, the system (FOIRE 3000) used in the present study provides only relative values of HbO and Hb (or nominal HbO and Hb). There are two implications for the relative value: first, it is the change with respect to the data at the time zero (when the recording starts); second, the value provided includes an unknown parameter L as a multiplying factor (e.g. L·HbO). The L is the photon average path length from the source to the detector, which does not only depend on the wavelength, but also varies from subject to subject, even from channel to channel for the same subject. In some CW setups, an estimated L might be used for each working wavelength [36]. But FOIRE 3000 does not provide such an estimate on L, instead, the L is simply included in the output values of HbO and Hb (such as L·HbO and L·Hb). In this case, one must be careful in averaging data over a group of subjects or even over channels for the same subject. As the L acts as a weight factor on the HbO (or Hb), averaging directly the output signal (e.g., L·HbO) over subjects may result in biased estimate on the average value. A useful way to overcome this problem is to transform the output signal S to the Z score before performing average over subjects (or channels). In fact, the Z score, Z=(S-mean(S))/std(S), is a measure of data with its own variance. By normalizing with the variance of S, the unknown parameter L is cancelled out in the Z score. Therefore, to achieve unbiased group average, in the data analysis we used the Z score for average instead of the nominal HbO (e.g., L·HbO) provided directly by the system.

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